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Handling uncertainties of hydrological loads in flood retention planning

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ABSTRACT The efficiency of technical measures for flood protection depends on the specifications of their design flood. If actual floods deviate from this design flood, the performance may differ significantly. To evaluate the remaining risk, a comprehensive hydrological analysis of flood conditions becomes essential. If multiple flood characteristics are considered, critical loads have to be characterised with multivariate statistics, providing an unprecedented wealth of information about the hydrological variability. However, such a characterisation involves many uncertainties. Using imprecise probabilities, these known unknowns can be integrated into the planning process. In this paper, the importance of multivariate imprecise probability data in flood protection planning is shown and a methodology to integrate this information into existing decision support frameworks is presented. To alleviate the utilisation of this data in the planning process, we propose a plausibility approach to filter the amount of possible flood scenarios and to improve the data accessibility. The application in a Multi Criteria Decision Making framework, which was developed for technical flood retention planning in a river basin, is demonstrated with a case study.

Keywords: Flood control planning; uncertainty analysis; imprecise probability; decision support; multivariate probabilities; MCDM.

1 Introduction

Flood risk management implies three aspects: risk analysis, risk evaluation and risk reduction. These aspects have a hierarchic order. Risk analysis is a precondition for risk evaluation and the need for risk reduction depends on risk evaluation. Decision makers are forced to accept risk as an indispensable criterion of making decisions, since an absolute protection against flooding cannot be reached by technical measures. The risk of failure of a dam which could result from the hydrological risk of an extreme flood which exceeds the design flood in interaction with other characteristics of operation and technical design (e.g. initial storage content, spillways etc.) is an example how this risk oriented design can be incorporated into dam safety analyses (Plate and Meon 1988). Similar assessments of the effectiveness of technical flood retention measures are needed, which have to consider possible consequences of insufficient performance under unusual conditions. Flood risk reduction depends on the efficiency of flood control measures and their reliability under manifold hydrological loads. However it is insufficient to specify floods scenarios without characterising their probabilities. In practice floods are characterised by the return period of the peak only. However, such a probabilistic characterisation is often insufficient for risk estimations of flood protection systems, as shown by recent flood events in Germany. The performance of technical flood retention facilities depend on multivariate characteristics of floods which have to be specified by several coinciding random variables such as flood peak, volume, shape and duration. It can be shown that flood protection may be ensured under favourable flood conditions, but in other cases the system may fail, even if a certain flood characteristic, e.g. the flood peak, remains below the value which was assumed for the design flood. An ensemble of hydrological loads can be applied to demonstrate under which conditions the performance of the planned flood control system may not suffice and to show impacts of possible failures. Yet to accurately describe the effectiveness of flood control measures, these hydrological scenarios have to be defined probabilistically. Multivariate statistics can be applied to calculate the probabilities of the relevant hydrological loads (e.g. De Michele *et al*. 2005; Grimaldi and Serinaldi, 2006; Klein, 2010).

Multivariate statistical characterisations demand large samples. Observed hydrological time series are often too short to extract such a representative sample of hydrological loads. This problem can be overcome by stochastic-deterministic flood simulation. It is based on a stochastic generation of precipitation events and a transformation of these precipitation fields with a deterministic hydrological model into runoff time series (e.g. Aronica and Candela 2007; Blazkova and Beven 2002, Blazkova and Beven 2004; Moretti and Montanari 2008, McMillan and Brasington 2008). This methodological approach implies many uncertainties (Lamb and Kay 2004, Cameron *et al*. 1999). A probabilistic characterisation of the results is difficult, as several stochastic interdependencies are incorporated. For example the meteorological load in its temporal and spatial distributions is uncertain as well as the initial state of the river basin (or the deterministic hydrological model which is used to represent it), the model parameters are uncertain, the behaviour of the model for extreme events, which are often higher than any observed flood, is uncertain, the impact of technical flood retention measures depends on unknown operation schemes and so on. These problems aggravate if such analyses are done for a large river basin with spatially distributed hydrological loads, where many different combinations of influencing factors are possible. To handle uncertainties, which result from insufficient statistical information or missing data, one can use imprecise probabilities instead of precise probabilities (Klir 1999). There are several options to express the imprecision of probabilities, e.g. by Random Sets or by Fuzzy Sets. In the following Fuzzy Sets are applied to characterise the uncertainties of hydrological loads.

The second component of risk, besides the probability of the hazard, is its consequence. These consequences depend on the intensity of the flood (e.g. water depth, flow velocity and duration of inundations) and the vulnerability of landscapes. The vulnerability differs with land-use, social structure, prosperity, season etc... Hence hydraulic 2-D modelling of flood events has to be combined with socio-economic analyses to estimate damages as second component of flood risk. An adequately selected set of hydrological scenarios would show a smooth transition from events where flood control may be ensured and no damage would occur to events where all attempts to control a flood may fail completely. The handling of this conflicting information in order to make an appropriate decision is a challenge for the decision maker. The decision maker is confronted with flood retention planning which differs in their performance between floods with multiple characteristics, triggering multiple failure mechanisms and causing a variety of effects. Multivariate statistics can be applied to characterise this complexity, but decision makers can often not handle them in an adequate way as multiple interpretations are possible (e.g. logical "and" or logical “or”). To alleviate this problem, we propose a plausibility approach to filter the amount of data and improve their handling.

Uncertain performance depending on multivariate hydrological loads is only one of many different problems of the complex decision making process in technical flood retention planning. Decision makers may differentiate for example between damages according to the spatial distribution, the frequency and options to get compensations. Simple cost- benefit relationships are insufficient if such aspects have to be considered. The benefits of flood control are uncertain as they depend stochastically on the occurrence of risky combinations of flood characteristics. On the other hand, the costs of flood control can be specified in detail. Uneven distributed burdens and benefits between upstream/downstream riparian communities pose yet another problem in the decision process. Here multi-objective analyses can be helpful for structuring flood management planning. These methods involve the quantification of objectives, the generation of alternatives and the selection of a preferred one. Multi-objective techniques can be classified into three groups of methods: methods for generating a non-dominated set of solutions, methods with prior articulation of preferences and methods with progressive articulation of preferences (Goicoechea *et al*. 1982). For flood management a prior, but flexible articulation of preferences seems to be most appropriate with regard to the multiple participants of the planning process. If protagonists get the opportunity to explore the decision space, to balance their weighting system under consideration of the possible outcome and to bring in their personal risk perception, then the result of such analyses are more likely to be accepted. Additional tools for aiding the flood retention decision process –such as the plausibility approach proposed here- should be integrated in the multi-objective techniques in order to keep the decision path practical.

2 Estimation of flood scenarios and their plausibility

2.1 Specification of the ambiguousness of return periods with copulas

A return period is a widely used statistical characteristic of any design flood. The classic point of reference concerning the frequency of a flood is the probability based on the flood peak. This characteristic alone is not sufficient to specify the performance of flood retention systems. The assumption that flood events with similar peaks but different volumes or different shapes will have the same probabilities as the flood peak is not correct. A more accurate estimation of the combined return periods of two or more variables requires multivariate analysis. Recently, copulas have been implemented in hydrological studies for bivariate frequency analysis. Salvadori and De Michele (2004) provide a general theoretical framework for exploiting copulas to study the return periods of hydrological events. In the work by Zhang and Singh (2006), copulas were applied for bivariate frequency analysis of flood peak and volume as well as duration and volume for two river stations. Since this paper focuses on the decision support, we will for brevity refrain from the mathematical descriptions of copulas. Detailed information on copula theory can be found in Joe (1997), Nelsen (1999), Favre *et al*. (2004) and Salvadori *et al*. (2007).

The issues a decision maker faces when confronted with multiple return periods can be described using an example from Klein et. al. (2010) (Fig. 1), where flood events from a stochastic-deterministically generated 10,000 year discharge time series have been analysed.

In Figure 1, the flood peak is depicted on the x-axis and the flood volume on the y-axis. It can be seen, a multitude of flood events can correspond with one single flood peak based return period. However the volumes of these flood events differ significantly. One can likewise calculate the probability in terms of flood volume, as indicated on the y-axis. The combined probability of exceedance of a certain volume and a certain flood peak can be determined using copulas or the bivariate probabilities as drawn in Figure 1.

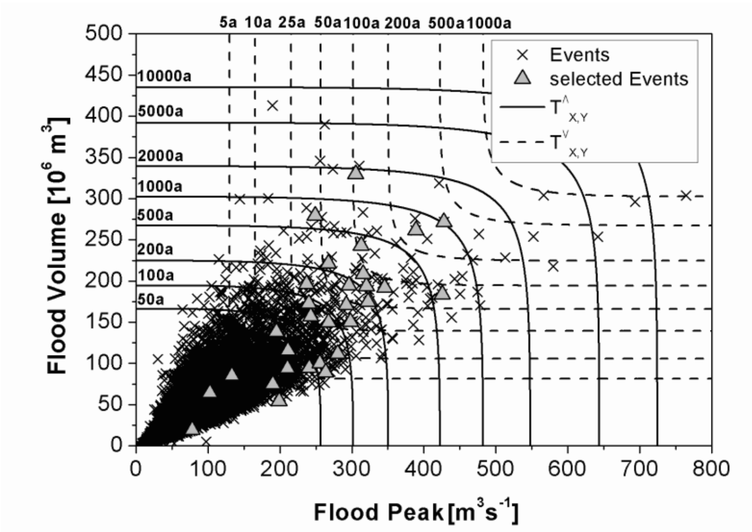

Figure 1 Differences in probabilities of the flood volume, flood peak and their joint "and" $T^{\wedge}_{x,y}$ & "or" $T^{v}_{x,y}$ probabilities (Klein *et al*., 2010)

To handle this ambiguousness of flood probabilities a methodology is required to support decision makers in combining the familiar peak-based probability and these emerging bi- and multivariate probabilities.

2.2 Unprecise probabilities and plausibilities

As mentioned above simulated data can be used to derive the data base of these multivariate frequency analyses. However, the results depend on the assumptions of the stochastic-deterministic modelling approach. All probabilities which are specified in this way are imprecise, as they depend on the way how they were estimated. Consideration of imprecision in expressing probabilities, which was strongly stimulated by Walley (1991), adds a new dimension to the formalization of uncertainty and uncertainty-based information. Walley demonstrated that reasoning and decision making based on imprecise probabilities satisfy the principles of coherence and avoidance of sure loss. To summarize the starting position: flood scenarios which results in different performances of flood retention facilities (reservoirs, polders) are specified by multivariate imprecise probabilities. These flood scenarios can be arranged into particular sets of floods according to the return period of their flood peaks. They differ in their other characteristics (e.g. volume or shape of the hydrograph). The interdependencies between the flood peak and other characteristics are considered with Copula statistics. The resulting statistical measures are used as additional information to specify the plausibility of these events. Multivariate probabilities are used here to differentiate between more and less plausible scenarios. Large differences between probabilities of different flood characteristics are indicators of non-plausible scenarios. If e.g. the flood peak has a return period of 10 years, but the flood volume has a return period of 100 years, in the traditional way the return period of the flood event would be defined by its peak with 10 years. This is obviously not plausible as the volume of this flood has a much smaller probability than its peak. The plausibility of an event with a certain return period of the peak is high if the deviations of the return periods of other characteristics are small. There are typical events where the return period of the peak and the return periods of other characteristics are similar and less typical events where these probabilities differ significantly. In this way, the decision maker retains the familiar peak-based probability and needs to incorporate only the concept of more and less plausible events in his judgements.

Since the specification of plausibility is uncertain, as the probabilities, which are used to derive it, are uncertain, these uncertainties can be specified by fuzzy sets. Fuzzy sets are an established way to consider uncertainties of set memberships (Klir and Smith 2001). The degree of membership of a single flood event to a set of scenarios with a certain return period of the flood peak can be specified by a triangular function. This degree of membership for each flood scenario is defined by the multivariate probabilities of its characteristics. This approach is consistent with the generalised theory of uncertainty in application of fuzzy sets for possibilistic modalities of generalised constraints (Zadeh 2005). Generally triangular fuzzy numbers are described by a triple of real numbers as $\tilde{A} = (l, m, u)$ where $l \leq m \leq u$ represent the lower, modal and upper value of the fuzzy number. The modal value has a membership value of $\mu_A(m) = 1$. In this study the highest value of the membership function ($\mu_A(u) = 1$) of hydrological load scenarios for inflows into a single reservoir was attributed to events where the bivariate copula probabilities between flood peak and volume are nearly the same as the univariate probability of the flood peak. Such flood events seem to be most representative for a certain return period with regard to the agreement of the different statistical characteristics of the flood. If e.g. the return period, which was estimated from the joint probability of peak and volume, is greater than the return period of the peak, the event is less probable than expected from the return period of the peak alone. If this concordance between return periods is not given, e.g. if the joint volume-peak-probability indicates a more frequent event, the return period of the flood peak seems to be less plausible. To consider these differences a characteristic "plausibility" $P_{Plausibility}$ is introduced, which can be derived from the differences in probabilities as it was discussed above in the following way, using the multivariate probability as a plausibility criterion:

$$P_{Plausibility} = \begin{cases} Min\left(\dfrac{T^{\wedge}_{Peak,Volume}}{T_{Peak}}; \dfrac{2 \cdot T_{Peak} - T^{\wedge}_{Peak,Volume}}{T^{\wedge}_{Peak,Volume}}\right), \forall T^{\wedge}_{Peak,Volume} \in \left[0; 2 \cdot T_{Peak}\right] \\ 0, \forall T^{\wedge}_{Peak,Volume} \notin \left[0; 2 \cdot T_{Peak}\right] \end{cases} \tag{1}$$

T_{Peak} and $T^{\wedge}_{Peak,Volume}$ are return periods estimated from flood peak statistics and from copula statistics of flood peak and volume, respectively.

3 Incorporating multivariate probabilities into Multi-Criteria Decision Making

3.1 Multiple criteria in flood planning

Often different objectives have to be considered simultaneously in flood control planning:

- Risk management demands the consideration of multiple consequences of floods. These consequences could be economic damages and the number of affected people but also impacts on the environment or the cultural heritage. Economic damages could be differentiated among industry, agriculture and population or between insured and not insured damages. Also the spatial characteristics of consequences have to be considered.
- The effectiveness of flood protection depends strongly on the location. The fraction of the controlled catchment is decreasing with the watercourse downstream of flood control systems. Thus the impacts of flood control on downstream reaches have to be considered in a spatial context.
- Costs of flood protection have to be differentiated between direct costs (e.g. construction costs) and indirect costs (e.g. regulations of land use in polders to prevent agricultural damages by regular inundations).

If flood scenarios are characterised by probabilities, the estimated consequences of floods can be characterised by the same probabilistic characteristics. The plausibility criterion, which was introduced here to characterise the hazard can be applied to differentiate between consequences.

In general it is difficult to consider probabilistic characteristics in Multi-Criteria Decision Making approaches (MCDM), yet if flood events with different hydrographs and different multivariate probabilities and their combinations are taken into consideration, decision making becomes, despite – or because of – the information gain, more demanding. Indeed, Yue *et al*. (2000) and Yue (2001) even list incorrect interpretation and misuse of multivariate statistic in the literature. In adding an extra "plausibility"-dimension we have transformed the multivariate imprecise probability problem into a two-dimensional probabilitistic description of flood scenarios: the flood peak based return period which is a well-known characteristic is flanked by the plausibility. Within each return period, not one single design flood is analysed, but a multitude of floods with varying plausibilities is considered. In some studies the expected values of flood damages are used. Such an approach is not appropriate as it was discussed by Merz and Thieken (2007). The expected value focuses mainly on floods with high probabilities but relatively low damages and disregards extreme floods with low probabilities but large consequences to societies. Therefore, we propose to allow the decision maker to vary the focus over entire the probability range specified by the main characteristic "flood peak return period" and to decide about the degree of plausibility he is willing to accept.

When introducing such a new methodology it is important to verify other steps of the decision process are not impeded and can function with the new information and its structure. Here two different MCDM-algorithms were applied in a case study, which consider the possibilistic and probabilistic measures in different ways: a distance based method (TOPSIS) (Hwang and Yoon, 1981) and a fuzzified version of the well-known AHP-method (Srdjevic and Medeiros, 2007). We have chosen this fuzzy, qualitative-oriented algorithm F-AHP to compare with the distance-base quantitative-oriented algorithm TOPSIS because both are used often in flood retention planning and because of their obvious differences. This allows us to test the applicability of integrating uncertain multivariate possibilities in flood control decision making, independent of the MCDM-algorithm.

3.2 A distance based MCDM tool – the TOPSIS approach

Many MCDM-tools are based on a comparison of Euclidean distances between the realizations of criteria of alternatives and a (hypothetic) idealized point which is defined by the optimal values of these criteria. The TOPSIS-method (**T**echnique for **O**rder **P**reference by **S**imilarity to **I**deal **S**olution), which was developed by Hwang and Yoon (1981) belongs to this group of methodologies. In contrast to other distance based methodologies as e.g. Compromise Programming, TOPSIS uses two quantities: the best alternative is located as close as possible to the ideal point (positive ideal situation: PIS) and as far as possible from the worst point (negative ideal situation: NIS). The advantage is that two alternatives with the same distance from the ideal point, but different distances from "NIS", can still be discriminated.

3.3 A fuzzified version of the Analytic Hierarchy Process method (FAHP)

The AHP-method (Saaty 1977, 1980) is based on a structuring of complex decision problems in a hierarchic way, where goals are subdivided into sub-goals. The criteria of alternatives are compared first in relationship to sub-goals, then the results of these comparisons are combined by a weighting of sub-goals to goals. Alternatives are compared pairwise for each criterion. The results of these comparisons are summarised in a symmetric matrix specifying the pair-wise relationships of alternatives with regard to one criterion. One advantage of AHP is the possibility to evaluate the consistency of subjective weightings of multiple objectives. There are two groups of subjective comparisons: the criteria have to be compared in their relative importance and the outcomes of alternatives have to be compared pairwise for each criterion. The uncertainties of these comparisons can be considered by fuzzy numbers. Srdjevic und Medeiros (2007) suggested a fuzzified version of the AHP-rating of Saaty, where the comparisons of the relative importance of criteria and the relationships between realizations are handled as fuzzy numbers. This Fuzzy-AHP- method (FAHP) combines the AHP- method of Saaty (1980) with the Fuzzy-theory of Zadeh (1965). It is an extension of AHP as it gives options to consider uncertainties in ratings and weights explicitly. However, the mathematical characterisation of consistency based on eigenvectors can not be applied if fuzzy arithmetics is used. Thus Saaty and Tran (2007) expressed their scepticism about fuzzifying crisp values and weights since this could decrease the consistency and worse, the validity of the outcome, unless good arguments for the fuzzification can be presented. However the fuzzy approach was chosen with regard to two aspects:

- as described before, the floods and consequences are characterised by plausibility which is estimated as a fuzzy number,
- the weighing of low or high probabilities can be described more flexible using fuzzy numbers characterising a bandwidth of probabilities the decision maker is focussing, instead of crisp numbers focussing on one specific probability and relate it to another one.

The result of the F-AHP is a single fuzzy number for each one of the alternatives, which can be used to compare it with other alternatives. There are several options to compare fuzzy numbers. The “Total Integrated Value” method (Liou and Wang 1992) provides the user extensive information about the lower and upper bounds of the fuzzy number. It is a flexible de-fuzzification method which obtains information about the sensitivity of the ranking with regard to the range of possible outcomes to the user.

5 Case Study

5.1 Study area

The methodology described above has been applied to the Unstrut river basin in the central part of Germany. The river basin has an area of around 6,400 km^2 and is situated in two different Federal States of Germany, upstream in the Federal State of Thuringia and downstream in the Federal State of Saxony-Anhalt (Fig. 2).

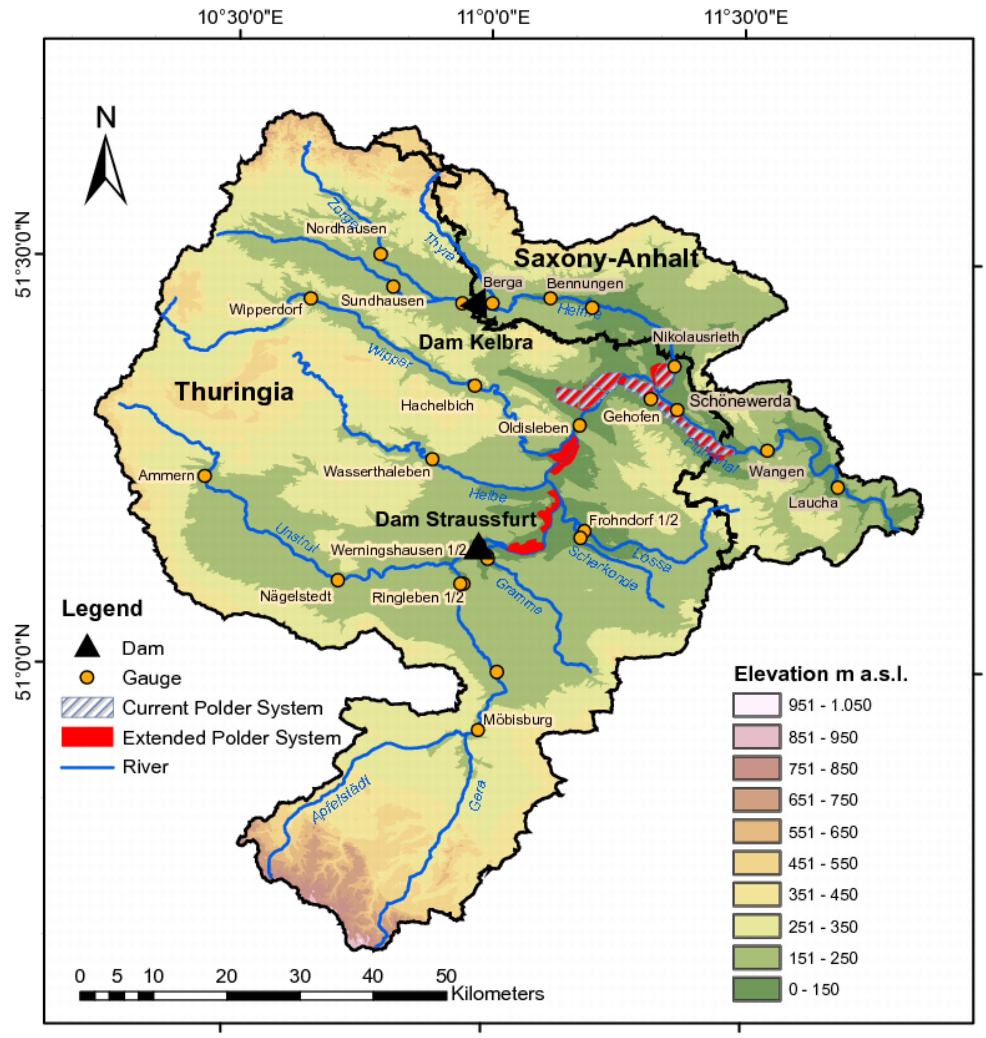

Figure 2 Topographical map of the Unstrut catchment in Thuringia and Saxony-Anhalt with components of the technical flood retention system (current and extended) and important gauges within the catchment.

The geographic location results in an uneven distribution of benefits and burdens of flood control. The upstream flood control system belongs to Thuringia, but a large part of flood protected areas are situated in Saxony-Anhalt. The catchment has a heterogeneous topographic structure, with lower regions in the central part, the Harz Mountains in the North and the Thuringian Forest in the South. At present the technical flood retention system within this river basin consists of the reservoir Kelbra and the reservoir Straussfurt, of some other smaller reservoirs of local importance, a flood channel and a flood polder system with five polders (see Fig. 2). In total the flood retention system has a volume of ~100 x 10^6 m^3.

The local planning authorities suggested a set of flood control measures, varying from the optimization of the existing polders, increase of retention time within polders by additional check dams to creation of new polders, alteration of the polder inlet structures and different types of inlet regulations (controlled and uncontrolled flooding). These measures were clustered into six states of the flood retention system. The “as-is” state is denoted as state 1 and the most complex state as state 6 (see Table 1).

Table 1 Planning states of the flood control system

State of the System	**Specifications**
SS1	As-is state. Only a small percentage of system retention capacity can be used due to malfunctioning technical elements.
SS2	As-is state but with working inlet structures. The polder system consists of polders Oldisleben, Kannawurf, Moenchenrieth, Artern and Wiehe and is fully operational; use of check dams.
SS3	Extension of the system. State 2 plus additional polders Riethgen, Waltersdorf, Soemmerda, Schluesselwiesen to increase the retention capacity.
SS4	Alternative extension of the system. State 2 plus additional polders Riethgen, Waltersdorf, Wundersleben, Scherndorf; increased retention capacities in comparison with state 3 plus new polders; the polder inlet structures are not controlled.
SS5	As state 4 but with controlled polder inlets.
SS6	As state 5 but with widened inlet structures of new planned polders.

5.2 Specification of hydrological loads and consequences

A long series of runoff (10,000 years) was simulated on a daily basis by coupling a stochastic rainfall generator and a deterministic hydrological model. For the parameter estimation of the stochastic rainfall generator 122 stations with observed daily values from 1961 to 2003 and for the calibration of the continuous rainfall-runoff model on daily basis discharge series from 1991 to 1996 were used. It has been shown that the statistical properties of the daily rainfall and the runoff were well reproduced (Hundecha *et al*. 2009). These data were essential for this study as the measured discharge data since the 1960's were affected by the construction of two flood reservoirs and river regulation works. Thus the long-term characteristics of the current flood regime could only be specified by simulations. A non-influenced inflow gauge situated upstream of the flood reservoir Straussfurt was used to verify the flood statistical results provided by the stochastic-deterministic simulations with the statistics of a series of 40 years measured discharge data. A representative sample of the population of possible flood events is required to evaluate a flood control system. Six different return periods were considered (T = 25, 50, 100, 200, 500, 1,000 years). Since the risk is not only related to the flood peak, as stated above, the selection of hydrological scenarios was further supported by cluster analysis of historical events to determine typical hydrograph shapes and volumes. In total 5 different hydrological scenarios were selected for each return period at the reference gage Straussfurt. Low-volume summer events, high volume spring floods, floods with multiple peaks, floods which are influenced by antecedent conditions of high soil moisture and floods with high spatial heterogeneity in precipitation were considered to characterise the large variety of hydrological loads. The results of multivariate statistical analyses of simulated data were used to characterise the multiple probabilities of these events (See Fig 1). Copula statistics were applied to estimate joint probabilities of the flood peaks and corresponding volumes at the inflows to the dams Straussfurt and Kelbra, as well as probabilities of coincidences of flood peaks at both reservoirs. A detailed description of the model selection and the copula analyse is given by Klein *et al*. (2010).

In Fig. 3 the inflow-outflow relationships of the two reservoirs for two different flood events with a return period of the peaks of 100 years are shown to demonstrate the necessity for a multivariate approach. Both events have a flood peak of about 300 m^3/s at the inflow to the Straussfurt reservoir. However, the hydrographs differ significantly.

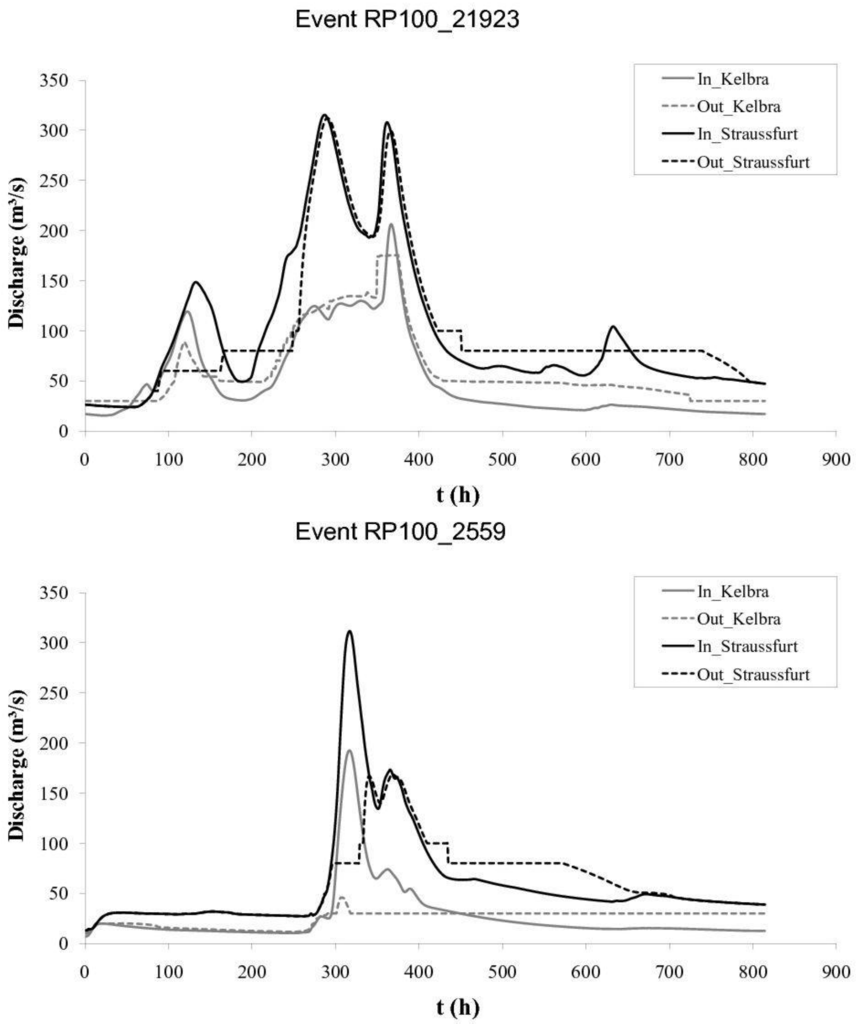

Figure 3 Inflow and outflow hydrographs of two flood events with a return period of 100 years (defined by the peaks) for the reservoirs Kelbra (North) and Straussfurt (South).

The flood event in the top of Figure 3 has a preliminary peak, two large main peaks and a large volume and can not be buffered significantly by both reservoirs. Therefore, this event would cause monetary damages that are 30 times higher than compared to the second flood (at the bottom), which is characterised by a hydrograph with a more regular shape and a moderate volume. The analysis of the bivariate copula probability of the flood peak and volume at gauge Straussfurt reveals that the flood with the large volume has a multivariate return period of 681 years, whereas the other flood has a bivariate return period of 134 years. In this case, although the probability of the peak flow is the same both events can be distinguished based on their plausibility: for an HQ100, the first event seems to be implausible.

After level pool routing in the two reservoirs the propagation of flood waves along the river course was simulated with a coupled 1-D/2-D hydraulic model which was able to consider the existing and planned polders (Kamrath *et al*. 2006). For 180 events (30 hydrological scenarios and six different states of the flood control system) the following characteristics were estimated: (i) inundation areas, (ii) maxima of water levels, (iii) maxima of flow velocity, (iv) the maxima of the products of water level and flow velocity, (v) the total duration of the flood events and (vi) the time of exceedance for certain water level thresholds. Operation schemes for reservoirs and polders were applied, which were based on analyses of the actual operation of the existing flood storage facilities or assumed for planned polders accordingly to the operation of existing polders. Costs and benefits of the planned measures were estimated. Here costs of operation and maintenance of polders, but also costs of temporary flooding of agriculturally used polders were considered. These costs were compared with potential reductions of damages. Since pecuniary damage varies with flood-specific parameters, the absolute values were estimated for each flood with land-use type specific damage functions. These functions specify the relative degree of damage, which can be expected from a certain hydrological load according to its water level, flow velocity and duration for a specific land use. The damage functions were combined with analyses of land use of inundation areas, which were provided by a Geographic Information System (GIS). With application of GIS it became possible to automate the calculation of geographically distributed economic risks and the number of affected persons as well as to specify vulnerable localities (e.g. schools, nursery homes, hospitals, cultural heritage etc.) which would be affected by a flood.

The inclusion of less plausible events demonstrates the ambivalent role of the flood control system. In Fig. 4 the reductions of flood peaks with system states 2 and 6 compared with the as-is-state of the system is shown. Under favourable conditions even peaks of very rare floods can be reduced. On the other hand the extended flood control system could have almost no impacts on floods with return periods of 50 years. Obviously such a more detailed specification of floods is helpful to characterise the efficiency of the flood control system.

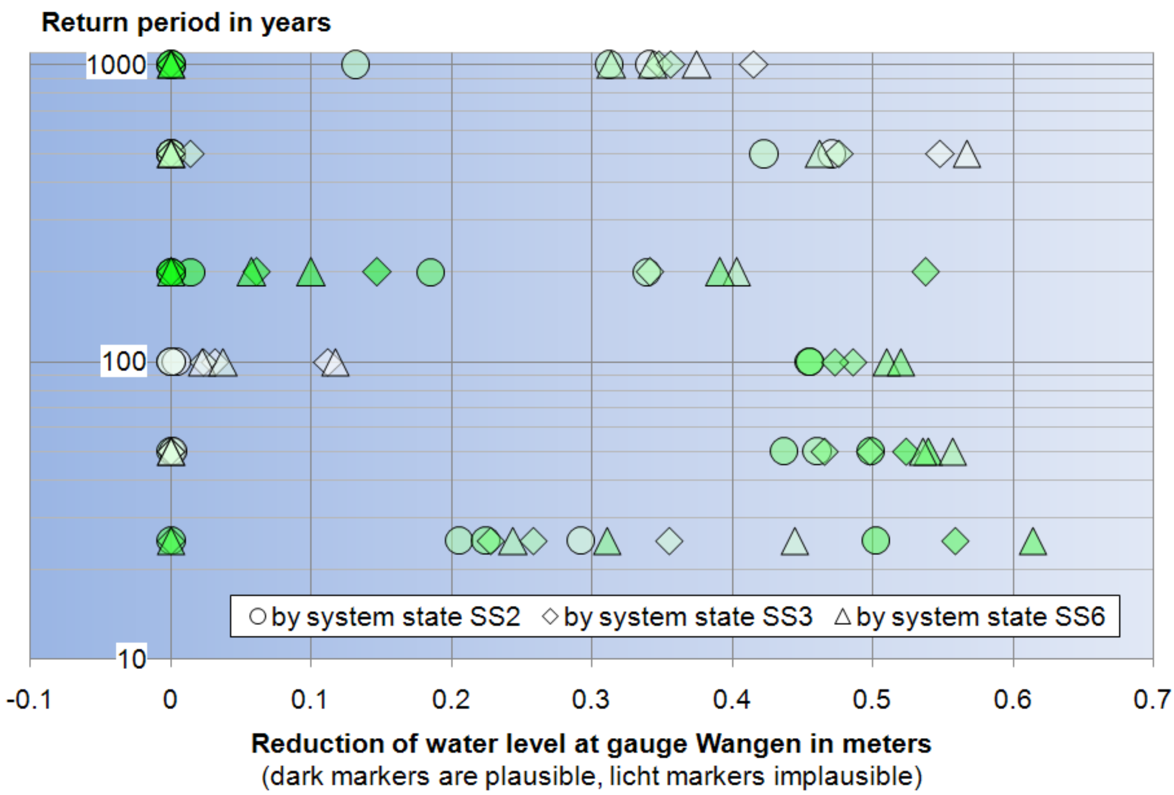

Figure 4 Reduction of the flood peak at the basin outlet Wangen

It became evident by hydraulic simulations that flood damages could be increased by new polders under unfavourable conditions if new polders are planned on natural retention areas. Especially for rare flood events the hydraulic conditions may be worsened by additional dykes. Even settlements may be affected if the volume-peak relationships are unfavourable and if new polders zoned by dykes disturb the flow paths in natural retention areas. The confrontation of decision makers with such possible impacts of floods with low plausibility increases their understanding of adverse side-effects. Even if the plausibility is low, such events could happen.

The plausibility of any single flood event was specified as it was discussed in paragraph 2 by Copula probabilities for peak and volume at the gauge Straussfurt. Based on this characterisation of plausibility for each set of five flood events with the same return periods of the peak the most plausible ones were identified. Together with the events with minimum plausibilities in both directions (where Copula based return periods are lower or higher than the return period of the peak) a fuzzy number was specified, which was used as a representation of the variability of floods for this return period. Based on these fuzzy numbers the damages and their plausibility ranges were described by triangular fuzzy numbers. An example of fuzzyfied damages is given in Figure 5.

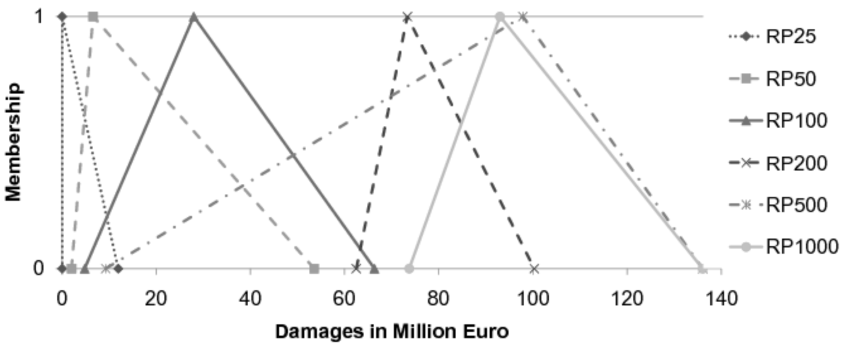

Figure 5 Fuzzy damages for the reference system („status quo“) for the return periods RP 25, 50, 100, 200, 500 and 1000 years.

5.3 Comparison of damages

As mentioned above the fuzzy damages were based on the plausibility of flood events. The same floods were used to evaluate the performance of all states of the flood control system in order to compare the changes in consequences of floods by different alternatives. The resulting triangular fuzzy numbers were compared using a relational operator *V* (Chang, 1996). It compares the modal values *m*, the lower (*l*) and upper (*u*) bounds of two triangular fuzzy numbers F_1 and F_2 and returns the following results $V(F_2 > F_1)$:

$$1 \quad if\ m_2 \geq m_1 \quad or \quad 0 \quad if\ l_1 \geq u_2 \tag{2}$$

and

$$\frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} \qquad in\ all\ other\ cases. \tag{3}$$

The last value specifies the intersection of the two fuzzy numbers F_1 and F_2, as it is shown in Figure 6.

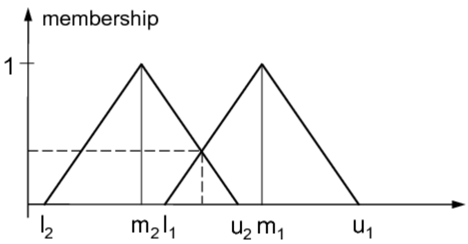

Figure 6 Comparisons of two triangular fuzzy numbers with intersection

Both values $V(F_1 \geq F_2)$ and $V(F_2 \geq F_1)$ have to be estimated to compare two fuzzy numbers completely. In every case one comparison of non-identical fuzzy numbers will result in the value „1“. In this case only the minimum of both results $V(F_1 \geq F_2)$ and $V(F_2 \geq F_1)$ is important. This intersection describes the possibility that both fuzzy numbers have a relationship $F_1 \geq F_2$, even if m_1 is smaller than m_2. If the operator returns the result „0“, this option can be excluded. To compare several triangular fuzzy numbers, pair-wise comparisons of fuzzy numbers are needed. One receives the degree of possibility that a convex fuzzy number F is greater than k other convex fuzzy numbers F_j (i = 1, …, k) by

$$V\left[\left(F \geq F_1\right) and \left(F \geq F_2\right) and \ldots and \left(F > F_k\right)\right] = min\, V\left(F \geq F_i\right)\left(i = 1,\ldots k\right) \tag{4}$$

This operator allows the comparison of different categories of damages for each return period and states of the flood control system. The result describes the degree of possibility that the alternative i will result in higher damages than all other alternatives j. An example is given for economic flood damages for different return periods in Table 2.

Table 2 Possibility that a certain state of the system (SS1 to SS6) would result in higher economic damages than all other alternatives, differentiated by return periods (RP in years)

SS	RP=25	RP=50	RP=100	RP=200	RP=500	RP=1000
1	0.167	0.167	0.196	0.095	0.144	0.085
2	0.167	0.167	0.196	0.082	0.142	0.085
3	0.167	0.167	0.151	0.116	0.152	0.106
4	0.167	0.167	0.153	0.237	0.188	0.242
5	0.167	0.167	0.152	0.234	0.187	0.239
6	0.167	0.167	0.152	0.236	0.187	0.243

These results can be interpreted as follows: For small return periods (RP = 25 and RP = 50 years) the states of the system are indifferent, all states perform in the same way. For flood scenarios with a return period of the flood peak of 100 years, the flood damages can be reduced by additional polders (SS3 to SS6). For more extreme floods (with return periods of 200 and more years) the risk of additional damages is more than doubled compared with states 1 to 3. The inclusion of implausible events demonstrated that modifications of the flood control system to reduce damages for low return periods have to be balanced against the increase of risks for events with higher return periods. In the next step the TOPSIS approach was applied to compare options and risks of the different states of the system.

5.4 Application of TOPSIS

As was shown above, at different locations within the river basin damages can be decreased by improved retention or increased by side-effects of polders. Here the distance-based evaluation of TOPSIS can be applied to differentiate between increased risk and opportunities for risk reductions. The resulting DSS considers 4 criteria (damage reductions, increases of damages, affected people and reductions of flood peaks downstream of the outlet gauge Wangen).

For all flood scenarios within one class of return periods and for all alternatives the Euclidian distances between the results and the optimal and worst values (minimal values for damages and maximal values for flood peak reductions) were calculated for each criterion. The Euclidian distances were summarised for each class of return periods. Since the standard version of TOPSIS does not allow calculation with fuzzy values, the plausibility of flood scenarios was used as a weighing factor to combine the five different floods. This way, the floods' effects are integrated proportionally into the TOPSIS-algorithm. Optionally, the decision maker can choose not to use the plausibility value proportionally but as a threshold to filter out or allow implausible events. Dynamically changing his threshold allows the decision maker to explore eventual changes of priorities. The decision maker then weights the importance of the different criteria and the return periods to combine these results. In Table 3 some results are shown to demonstrate the flexibility of the TOPSIS results in relationship to different weightings.

Table 3 TOPSIS-distances of system states, optimal is the maximum (numbers printed in bold)

Main Goal	SS1	SS2	SS3	SS4	SS5	SS6
Reduction of flood peaks at the basin outlet						
all floods	0.013	0.603	**0.899**	0.825	0.831	0.868
focus on frequent floods	0.008	0.717	**0.883**	0.873	0.839	0.943
focus on rare floods	0.017	0.583	**0.947**	0.821	0.812	0.822
Damage reduction in the Unstrut basin upstreams Wangen						
all floods	0.023	0.507	**0.819**	0.829	0.842	0.830
focus on frequent floods	0.015	0.431	**0.847**	0.862	0.872	0.865
focus on rare floods	0.030	0.586	0.772	0.797	**0.811**	0.798
Increase of damages in the Unstrut basin upstream of gauge Wangen						
all floods	**0.994**	0.809	0.271	0.155	0.219	0.185
focus on frequent floods	**0.993**	0.742	0.185	0.144	0.252	0.204
focus on rare floods	**0.994**	0.860	0.325	0.153	0.169	0.154
Combined goals: flood peak reduction, damage reduction, increase of damages						
all floods	0.550	0.562	**0.581**	0.517	0.539	0.516
focus on frequent floods	0.509	**0.546**	0.532	0.524	0.536	0.528
focus on rare floods	0.575	0.598	**0.613**	0.509	0.521	0.496

The optimal distance value in each category is „1“ (greatest distance from negative ideal situation: NIS). If the most important goal is flood protection downstream, measures with additional polders would be selected. One receives the same result if damage reductions within the river basins would be given priority in planning. If the risk of additional damages will be emphasised, all additional polders would be refused. If these three targets are combined with equal weights the differentiation between the alternatives becomes more difficult. This analysis proves that the plausibility approach is compatible with the well-known TOPSIS-algorithm either as a proportional weighing system or as a threshold filter..

5.5 Application of Fuzzy-AHP

To apply F-AHP the decision criteria have to be arranged hierarchically into goals and sub-goals. Here 5 hierarchic levels, which are shown in figure 7, were applied. The flood scenarios were differentiated first of all by their return period classes which were specified with the flood peak at the most central gauge of the river basin (gauge at the inflow into the Straussfurt reservoir). Costs were differentiated into two parts, the costs of construction and the losses of agriculture (crop failures) if polder areas are flooded. The benefits of the alternatives are specified into reductions of flood damages (here damages in settlements and damages outsides are considered separately), of flooded areas, affected people and reductions of the water level at gauge Wangen.

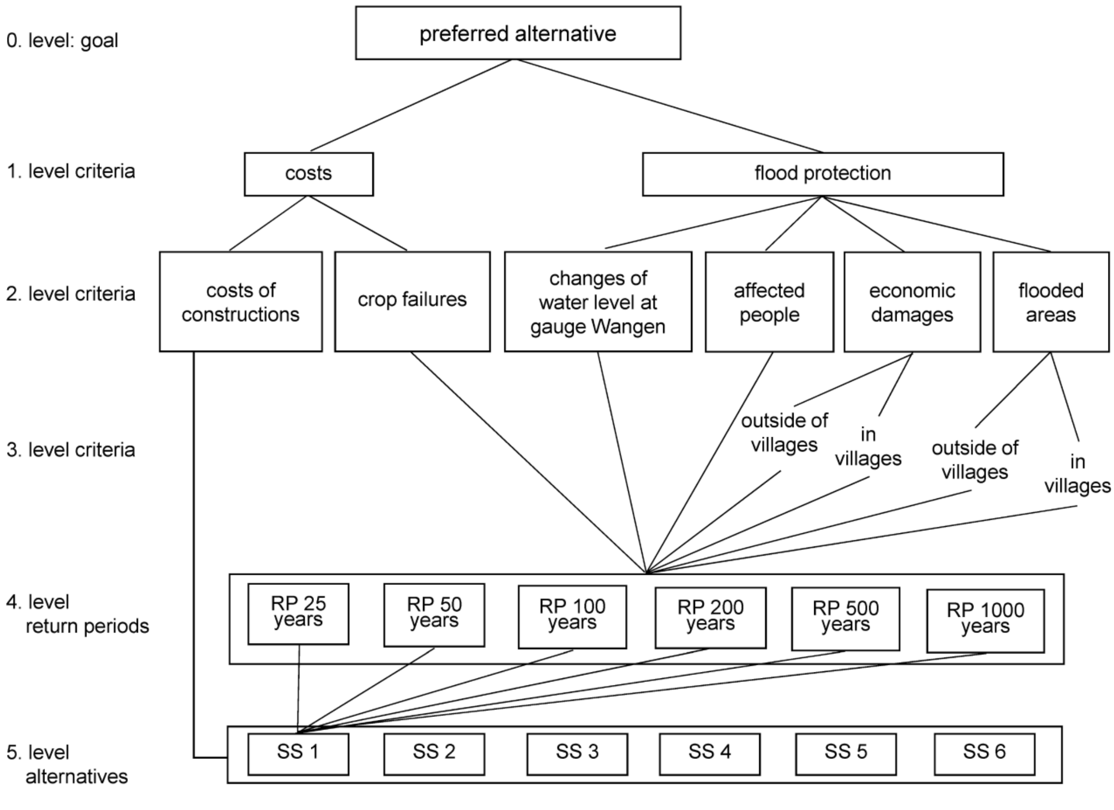

Figure 7 Hierarchic structure of the FAHP-approach. For clarity, the links between level 4 and 5 are only drawn for SS1.

The decision maker has to specify his priorities by a weighting of the criteria. This is done by a pair-wise comparison of two criteria with fuzzy-numbers according to figure 7. This weighting can be modified if the decision maker explores the decision space interactively.

Other weightings which were included in the developed Decision Support System (DSS) are:

1. Weighting by return periods (fourth level): All return periods can be weighted equally, higher weightings of rare or of frequent events are possible (frequent events are events with return periods of the peak from 25 to 100 years). Three options are offered.
2. At the third level damages can be weighted according to their locations. Three options are possible: higher weighting of damages outside of settlements or of damages within settlements, or an equal weighting of these areas (three variants).
3. At the second level the criteria of „flood protection“ can be weighted in seven variants. Focus can be given on the following components:

    a. economic damages

    b. flooded areas

    c. affected people

    d. changes of water level at gauge Wangen

    e.- g. focus on changes of water level at gauge Wangen plus one of the criteria mentioned under a.) to c.)

4. For the criterion “cost” in the second level a higher weight could be given to construction costs or to losses of agriculture. Agricultural losses were specified not by expected values, based on integration of all flood probabilities, but with losses which were derived from the applied flood scenarios. The seasonal variability of agricultural damages was considered.

5. With regard to the possible combinations three variants of weighting were offered: At the first level a higher importance could be given to costs or to flood protection efficiency. Both criteria could be weighted equally or one could be emphasized.

In total 567 combinations are possible (3·3·7·3·3), which can be specified within the DSS interactively. All criteria were provided as triangular fuzzy numbers for each alternative. As a result fuzzy numbers are estimated which have to be defuzzified to describe the relative performance of each alternative compared with all other alternatives. The pair-wise comparison of two alternatives was done after the defuzzification of these numbers. Here the „Total Integrated Value“ method was applied to weight the three elements of the triangular fuzzy number according to a parameter λ. This weighting considers the degree of optimism of the decision maker. The parameter value λ=0.5 is applied if the decision make is unbiased towards risk. An optimistic decision maker will choose a value of λ>0.5, a risk-adversive decision maker a value below 0.5. The comparison of alternatives was based on fuzzy numbers. Fuzzy numbers were applied also for the weighting of the criteria. The effect of the choice of the parameter λ is demonstrated in table 4 for the main "goal flood protection" with a focus on "economic damages", an equal weighting of "damages within and outside of settlements" and equal importance of all floods without consideration of their return periods. In this example the system state 2 would be preferred; however, the differences between the system states 1 to 3 and 4 to 6 are small if the upper bound of the resulting fuzzy numbers is not considered (λ=0). This ability to vary between optimism and risk-aversion allows the decision maker include or exclude implausible floods with extreme high or low damages.

Table 4 Impact of the parameter λ on defuzzification of the results of FAHP

λ :	**SS1**	**SS2**	**SS3**	**SS4**	**SS5**	**SS6**
0	0.11	0.12	0.11	0.06	0.07	0.07
0.5	1.90	2.01	1.91	1.21	1.58	1.40
1	3.70	3.91	3.72	2.36	3.10	2.73

Results of the FAHP approach for a parameter value of λ=0.5 are presented in Table 5.

Table 5 Results of the Fuzzy-AHP approach with focus on flood protection and equal weighting of damages at settlements and non-populated areas, Defuzzification with the Total Integrated Value (λ=0.5), optimal is the maximum (numbers printed in bold)

Main Goal	**SS1**	**SS2**	**SS3**	**SS4**	**SS5**	**SS6**
Reduction of flood peaks at the basin outlet						
all floods	1.11	1.27	**1.50**	1.15	1.25	1.19
frequent floods only	0.78	0.95	**1.06**	0.95	1.04	0.99
rare floods only	0.91	0.97	**1.19**	0.78	0.84	0.78
Damage reductions in the Unstrut basin upstream gauge Wangen						
all floods	1.90	**2.01**	1.91	1.21	1.58	1.40
frequent floods only	1.30	**1.47**	1.28	1.07	1.40	1.20
rare floods only	**1.55**	**1.55**	**1.55**	0.72	0.94	0.85
Combined goals: flood peak reduction, damage reduction, increase of damages						
all floods	1.44	**1.57**	**1.57**	1.06	1.28	1.18
frequent floods only	1.01	**1.18**	1.07	0.91	1.10	0.99
rare floods only	1.16	1.20	**1.28**	0.67	0.80	0.75

As shown, the additional plausibility information can easily be integrated into the FAHP methodology. A comparison of the results of both methodologies (TOPSIS and FAHP) demonstrates similarities and differences:

- With the main goal of a reduction of flood peaks at the basin outlet FAHP clearly prefers System State 3. TOPSIS differentiates here between rare and frequent floods. For frequent floods, additional polders with large inlet structures are preferred (System State 6) (the different plausibilities of flood events were used as weighing-factors according to their membership values).

- If damage reductions within the Unstrut basin were chosen as the main goal, FAHP sees no need for additional polders but prefers the version SS2 (repaired inlet structures for existing polders). Here the damage reductions and possible increase of damages were not considered separately. TOPSIS would prefer additional polders (System State 5) under consideration of possible flood damage reductions within the basin but refuse them if the focus is directed on the possible increase of damages (also SS 2 is preferred in this case).

- For a combination of the two goals “flood peak reduction at the outlet” and “damage reduction within the basin” both methods deliver nearly the same results. Preference is given to System State 3 under consideration of all floods, with focus on frequent floods to System State 2 but with special emphasis to rare floods System State 3 would be preferred.

6 Conclusions

Risk oriented planning depends strongly on the information which can be used to specify hydrological risk. With regard to the limited technical capacities for flood protection the remaining risk of such systems should be identified. Multiple examples were given where the flood peak as a sole characteristic proved insufficient to identify the actual risks. A better suited specification was proved to be a consideration of multiple flood characteristics, which are of utmost important for adequately testing the functionality of technical flood retention systems. The combination of these characteristics makes the difference between system failures and effective flood control. Flood scenarios with a probabilistic characterisation through multivariate statistics can be applied to improve flood control planning with special emphasis on possible failures and remaining risks. The application of multivariate statistics demands a large data base, which can be derived from simulations with a coupling of stochastic and deterministic models. However, the results will be uncertain and the derived statistics should be handled as being uncertain as well. This can be done with "imprecise probabilities". To reduce the information overload for decision makers due to uncertain multivariate probabilities, a methodology was developed based on a plausibility approach. This approach allows the decision makers to retain the classical flood peak based return period and incorporates the other crucial flood characteristics in a plausibility index. The applicability of the methodology was tested in a case study. The new plausibility data were integrated in two strongly differing Multi-Criteria Decision Making frameworks and the results were compared. Because of the inclusion of implausible events, the side-effects of flood protection measures became obvious in both methodologies. The two different MCDM algorithms TOPSIS and F-AHP work well with the extra plausibility information and it was shown that results with common goals are similar. This demonstrates the practical value of the proposed methodology.

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